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# Hardware Implementation of Closed Loop Speed Control of Separately Excited DC Motor using CUK Converter

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***Abstract: This paper describes the hardware implementation of speed control of Separately Excited DC motor using DC-DC converter. The DC-DC Cuk converter has been designed for required variation in the output voltage according to which the speed control of the given DC motor is achieved. PWM (Pulse Width Modulation) technique has been designed using analog circuit with OPAMP LM318 to achieve the output variation in the voltage of the CUK Converter which is directly fed into the armature of the Separately Excited DC Motor. Further, the closed loop speed control is achieved using PID controller. The simulation model of the proposed model is also designed and executed using MATLAB.***
***Keywords: CUK Converter, Separately Excited DC Motor, PWM (Pulse Width Modulation), PID Controller.***

## I. INTRODUCTION

An electrical DC drive basically consists of combination of controller, converter and DC motor. Here, the DC-DC CUK converter is used to control the armature voltage. The basic principle behind DC motor speed control is that the speed of DC motor can be varied by controlling armature voltage keeping field voltage constant for speed below and up to rated speed. The output speed is compared with the reference speed and error signal is then fed to speed controller. If there is a difference in the reference speed and the feedback speed, the controller output will vary. The output of the speed controller is the control voltage that controls the operation duty cycle of converter. The converter output gives the required voltage to bring motor speed back to the desired speed. The controller used in a closed loop model of DC motor provides a very easy and common technique of keeping motor speed at any desired set-point speed. In a closed loop speed controller, a voltage signal is obtained from the sensor attached to the rotor shaft which is proportional to the motor speed is fed back to the input where signal is subtracted from the set-point speed to produce an error signal. This error signal is then fed to the controller to make the motor run at a desired speed. The speed of DC motor can be adjusted above or below rated speed. The speed above the rated speed is controlled by field flux control and speed below the rated speed is controlled by armature voltage control. Here, the speed control of Separately Excited DC motor is achieved below the rated speed using armature voltage control method.

## II. LITERATURE SURVEY

Rheesabh Dwivedi et. al have worked on the parametric variation analysis of non-isolated Cuk converter for constant voltage applications considering inductor and capacitor as performance parameters. The different values of inductors and capacitors were taken for carrying out the simulation and observing the results. The modeling has been done in the Continuous Conduction Mode (CCM). A PI (Proportional Integral) controller has also been designed in the closed loop for controlling the output voltage for constant voltage applications [1]. Nabil. A. Ahmed have worked on the dc-dc buck-boost converter fed DC motor using uniform PWM technique. The MATLAB simulation and modeling for steady state and transient analysis of Separately Excited DC motor was done. The performance of the converter is being analyzed, clarified with the PWM control strategy and the DC voltage control [6]. Jaafer Sadiq Jaafer et. al have described the speed control of a Separately Excited DC motor using chopper as a converter and PI as a speed and current controller. Armature voltage control method for speed control was used here which can be done for controlling a speed at rated and below the rated speed [7]. Jide Julius Popoola et. al have developed a Simulink model of armature voltage control of DC motor. The analysis and performance evaluation of the DC motor have been done on the simulation and the effect of armature voltage on the armature voltage-speed characteristics and torque-speed characteristics of the armature controlled DC motor have been studied. Furthermore, the results of the study showed that the speed of the DC motor is directly proportional to the armature voltage [8]. Sanket A. Asarkar et. al have presented a work on how the different parameters of the Separately Excited DC motor can be identified experimentally. In this paper, the different experimental procedure has been given for determining the DC motor parameters. The simulation of the closed loop speed control of Separately Excited DC motor has been done using a PI controller [2].

## III. PROPOSED MODEL

### A. *Experimental Framework*

The proposed set up for the speed control of Separately Excited DC Motor has been shown in the figure. The required DC supply for the input of CUK Converter is being fed from the 220V DC supply available in the Electrical Drive Lab available in the college. Further, the PWM (Pulse Width Modulation) technique a widely used technique for speed control is being designed using a OPAMP LM 318 and GATE Driver circuit has also been designed using the OPTO-COUPLE MCT 2E as discussed in the section 1) and section 2) below respectively. Moreover, the PID Controller has also been designed using OPAMP IC741 and Hall Effect speed sensor has been used in our model for motor speed detection.

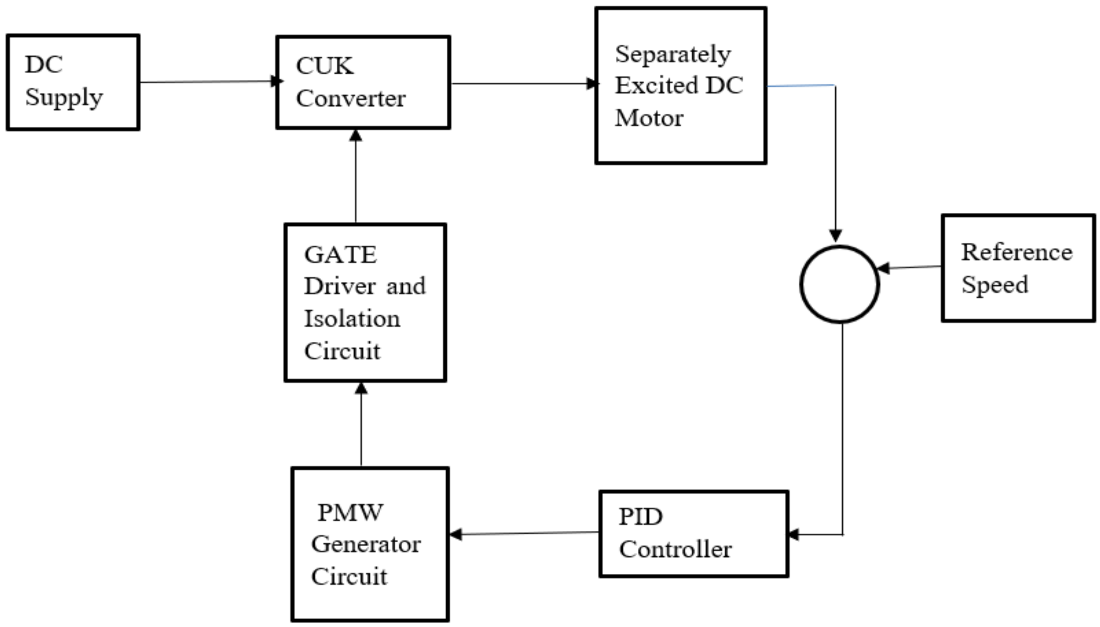


Fig. 1 Schematic block diagram of Closed Loop Speed Control of Separately Excited DC Motor

## IV. METHODOLGY

1) *Design of PWM (Pulse Width Modulation) Generator Circuit:* The PWM signal has been generated by using OPAMP LM318 by comparing the DC voltage with the triangular wave as shown in the figure. The reason for choosing OPAMP LM318 over IC741 is because the OPAMP IC 741 has a very low slew rate and it does not work well at higher frequencies. The frequency of the PWM pulse is same as that of the triangular wave.

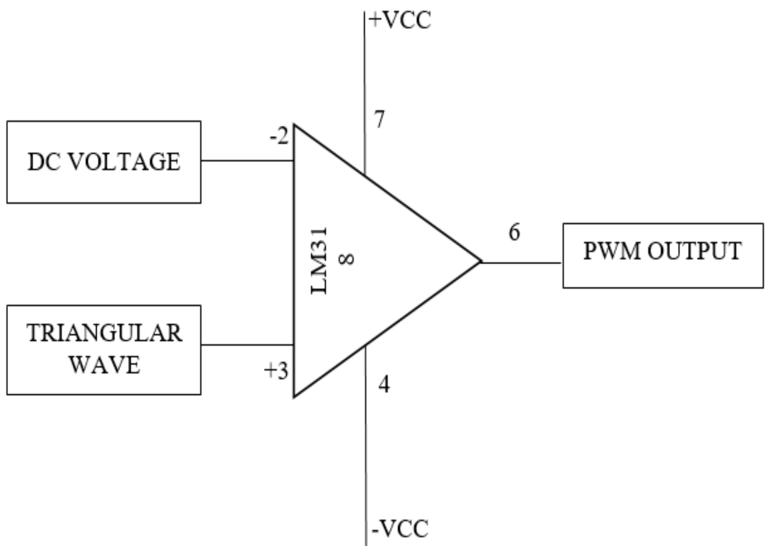


Fig. 2 PWM Generator circuit using OPAMP LM318

2) *Gate Driver and Isolation Circuit:* The gate driver and the isolation circuit is shown in the figure below. First the PWM pulse generated from the opamp with a peak-to-peak voltage of the pulse 12V is being given to the +5V voltage regulator IC 7805 to get output PWM pulse with peak to peak voltage of the pulse as 5V. The grounding of the pulse generator circuit and that of the optocoupler MCT2E has been kept same with the pin no. 2. The rectifier circuit of 15V has been designed to give the supply to the pin no. 5 of optocoupler. The grounding of the rectifier circuit and the grounding of converter circuit has been kept same for the isolation. The output PWM signal is then taken from the pin no.4 of the optocoupler with a peak-to-peak voltage of the pulse with 14.5V for triggering the MOSFET.

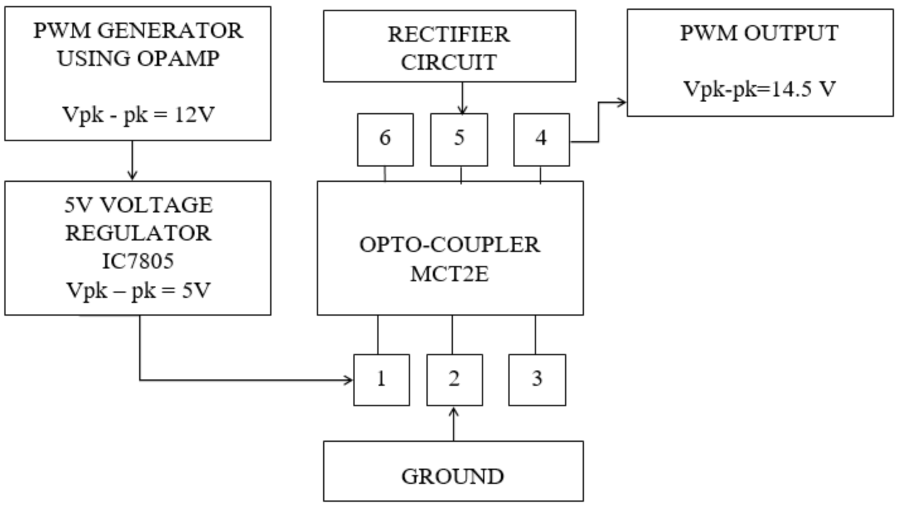


Fig. 3 Gate driver and isolation circuit using optocoupler MCT2E.

### A. *Separately Excited DC Motor*

The following figure shows the schematic circuit diagram of Separately Excited DC motor:

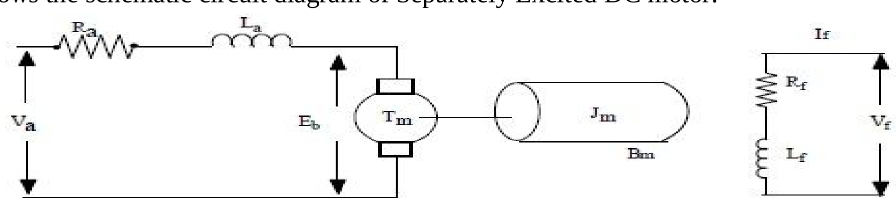


Fig. 4 Schematic Circuit Diagram of a Separately Excited DC Motor.

The various parameters of the separately excited DC motor [3]-[7] are shown below:

$T_m$= Motor torque or electrical torque.
$B_m$= Viscous friction coefficient.
$J_m$= Total inertia of the motor.
$V_f$= Field excitation of the motor.
$R_f$= Field resistance.
$I_f$ = Field current.

At the steady-state, the voltage equation of separately excited DC motor is given by,

$$V_a = I_a R_a + E_b \tag{1}$$

Where, $V_a$ = Armature voltage in volts.
$I_a$ = Armature current in Amperes.
$R_a$ = Armature resistance in Ohms.
$E_b$ = Back EMF (Electromotive Force).

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The back EMF equation is further given by,

$$E_b = k\emptyset N \tag{2}$$

Where, $k$ is a constant decided by the design of the machine (total no. of conductors, no. of parallel paths and no. of poles) and $\emptyset$ is the field flux and $N$ is the speed of DC motor in rpm. Using equations (1) and (2), the speed equation for separately excited DC motor is given by,

$$V_a = I_c R_a + k\emptyset N \tag{3}$$

Simplifying further,

$$N = (V_a - I_a R_a)/k\emptyset \tag{4}$$

The speed control of a separately excited DC motor using armature voltage control technique can be done only for a speed below and till the rated speed. The rating of the separately excited DC motor chosen in [3] is 1HP, 220V, 1500rpm and field 220V, 0.25A .

1) *Parameter identification of Separately Excited DC motor:* The Separately Excited DC motor has been chosen with the ratings: 1Hp, armature: 220V, 4A, field : 220V, 0.25A, 1500 RPM, CLASS F insulation. The parameters of the Separately Excited DC motors have been identified experimentally [2]-[3] as follows:

*a) Measurement of Armature and Field Resistance*

The following is the circuit diagram used for determining the armature and field resistance:

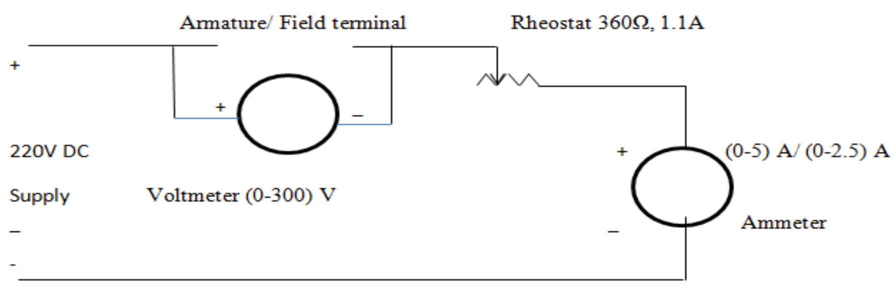


Fig. 5 Circuit diagram to determine the armature resistance and field resistance.

To determine the armature resistance, firstly the 220V DC voltage is supplied to the armature terminal of the Separately Excited DC motor as shown in the above figure. A voltmeter of ratings 0-300V is connected across the armature terminals of the DC motors and a rheostat of 360 Ω, 1.1 A is connected in series with the ammeter as a protection so as to avoid the damage in the armature windings from the high current and thus voltage across the armature terminal and current is being noted down as shown below:
At voltage V1= 4.5 V, the current I1= 0.5A and at voltage V2= 5 V, the current I2=0.6A. So, now the armature resistance calculated is found to be 9Ω. Similarly, the field resistance is found to be 857.

*b) Measurement of Armature and Field Inductance*

The following is the circuit diagram used for determining the armature inductance and the field inductance:

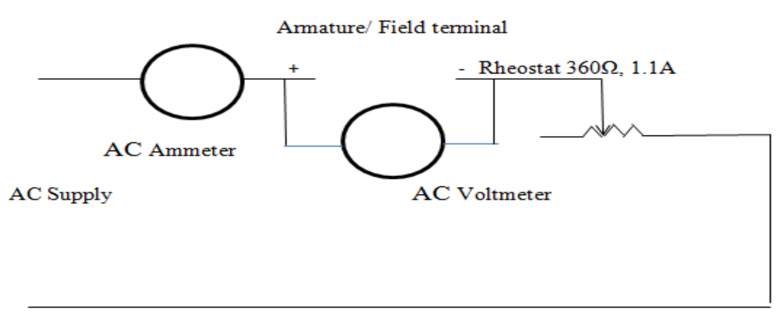


Fig. 6 Circuit diagram to determine the armature and field inductance.

To determine the armature inductance and the field inductance of the DC motor, firstly the small AC voltage is supplied to the armature and field terminals of the separately excited dc motors. The AC voltmeter is connected across the armature terminals and an ammeter and rheostat is being connected in series as shown in the above figure. The following calculations were done for determining the armature and the field inductance:

For armature inductance:

Voltage, V1=18V and current, I1 = 0.393A. The impedance Z= V1/I1 =45.8Ω. Now, the formula for calculating the reactance is given by,

$$X = (Z^2 - R_a^2)^{1/2} \quad (5)$$

$$X = (45.8^2 - 9^2)^{1/2}$$

Also, $X = 2\pi f L_a$ (6)

Where, $f$ is the frequency and $L_a$ is the armature inductance. So, $L_a$ is found to be 0.146 H. Similarly, the field inductance is found to be 2.1227 H.

***c)*** *Measurement of Inertia (J)*

To measure the inertia of the DC motor, first the DC motor is first made to run at the rated speed of 1500 rpm by varying the armature rheostat. When the motor has reached its rated speed, the supply to the motor is disconnected and the time taken for the speed to fall from 1500 rpm (N1) to 1000 rpm (N2) without load, t1 is noted down. Now, the certain amount of load is given to the motor and time taken for speed to fall from 1500rpm to 1000rpm with load, t2 is also noted down. The voltages V1 and V2 under loaded conditions are also noted down and currents I1 and I2 are also noted down both at 1500rpm and 1000rpm.

The inertia of the motor is evaluated from the following expression:

$$J = V_{av} I_{av} \left(\frac{t1.t2}{t1-t2}\right) \frac{1}{N_{av}} \left(\frac{60}{2\pi}\right)^2 \frac{1}{\Delta N} \quad (7)$$

Where, Vav =(V1+V2)/2
Nav = (N1+N2)/2
N = N1-N2
Iav = (I1+I2)/2

By substituting the values in equation, the value of inertia constant (J) is calculated.

2) *Designing of PID controller using OPAMP IC 741:* The following diagram shows a PID controller using OPAMP IC 741 for low error voltage application. The Hall Effect speed sensor has been used in our closed loop model. The Controller compares a measured value from a actual motor speed with a reference set point value. The difference of the value is then sent to the PID controller that brings the process measured value back. to its desired set point. Unlike simpler control algorithms, the PID controller can adjust process outputs based on the history and rate of change of the error signal, which gives more accurate and stable control [4].

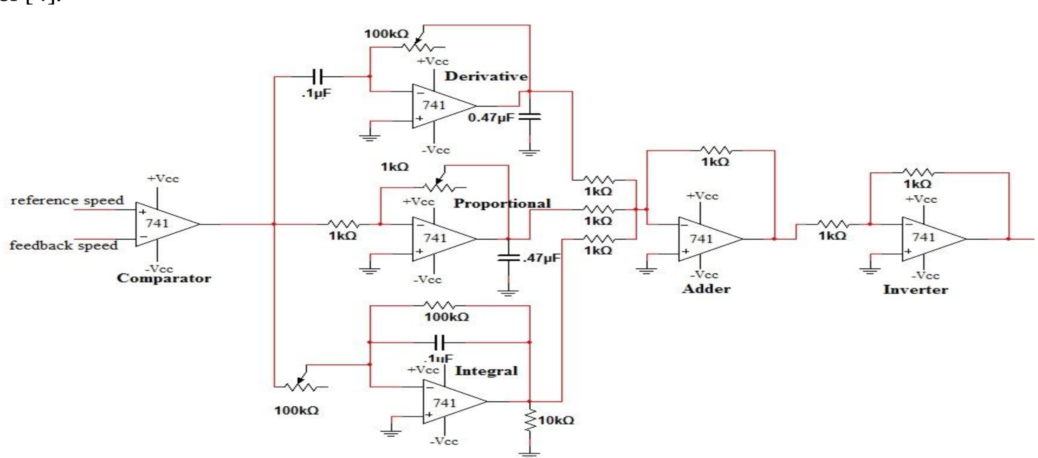


Fig. 7 PID controller circuit diagram using opamp IC741

 

### *B. Designing of Cuk Converter for 220V DC Motor*

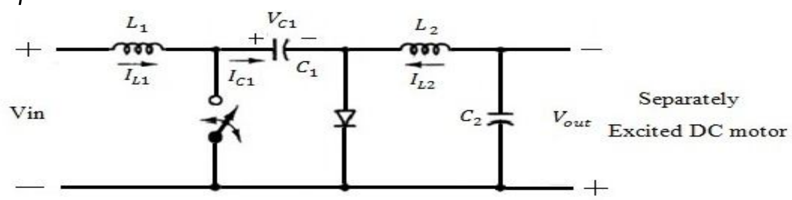


Fig. 8 DC-DC Cuk Converter with Separately Excited DC Motor

The systematical method of designing the elements of Cuk converter and the detailed mathematical analysis of Cuk converter have been done emphasizing on the design consideration considering key factors. The various design equations and parameters of the Cuk converter are shown considering Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) [1]. The values of the components calculated in [3] for designing DC-DC Cuk converter for 220V DC motor are as follows:

Switching frequency of the pulse = 25 KHz.

*1)* L1= 18mH, Current rating = 4A
*2)* L2= 15mH, Current rating = 4A.
*3)* C1= 200µF, Voltage rating = 450V.
*4)* C2= 280µF, Voltage rating = 450V.

The assumed values of peak to peak ripples values of inductor current are $I_{L1}$= 0.16A and $I_{L2}$= 0.19A. The input voltage given is 110V. The output voltage is variable from 0 to 220V DC by varying duty cycle of the PWM pulse width. Experimentally, the switching frequency of the pulse is kept at 8.3 KHz whereas $L_1$ = 18mH and $L_2$ = 15 mH are kept same but $C_1$ and $C_2$ are chosen as 47µF , and 100µF .

### *C. Simulation of closed loop speed control of Separately Excited DC motor*

The following MATLAB Simulink model shows the closed loop speed control of Separately Excited DC motor using Cuk converter. The reference speed is compared with the actual speed of the motor and given to the input of the PID controller. The PID controller is being designed to track the reference speed of the motor. The appropriated values of the gains Kp, Ki and Kd of the PID controller are adjusted to 22.5, 5 and 5 respectively.

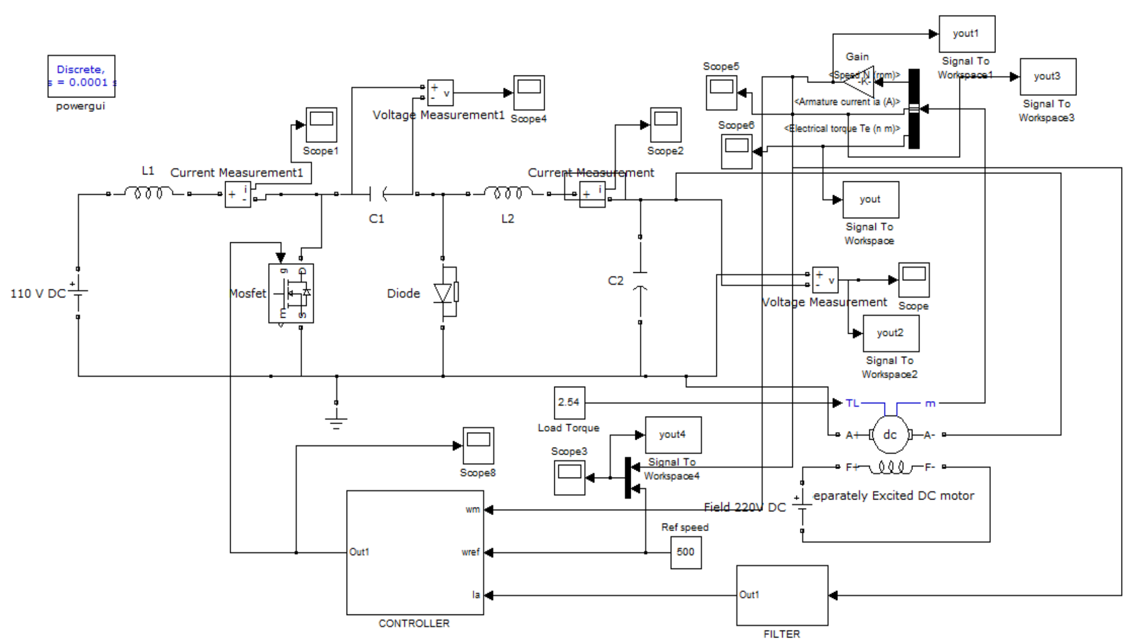


Fig. 9 MATLAB Simulink model of Closed loop speed control of Separately Excited DC motor using Cuk Converter.

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## V. RESULTS

### *A. Simulation Results*

The Simulation results of Closed Loop Speed Control of Separately Excited DC motor are as shown below:
Reference speed = 1000 rpm.
Tracked speed = 1000 rpm.

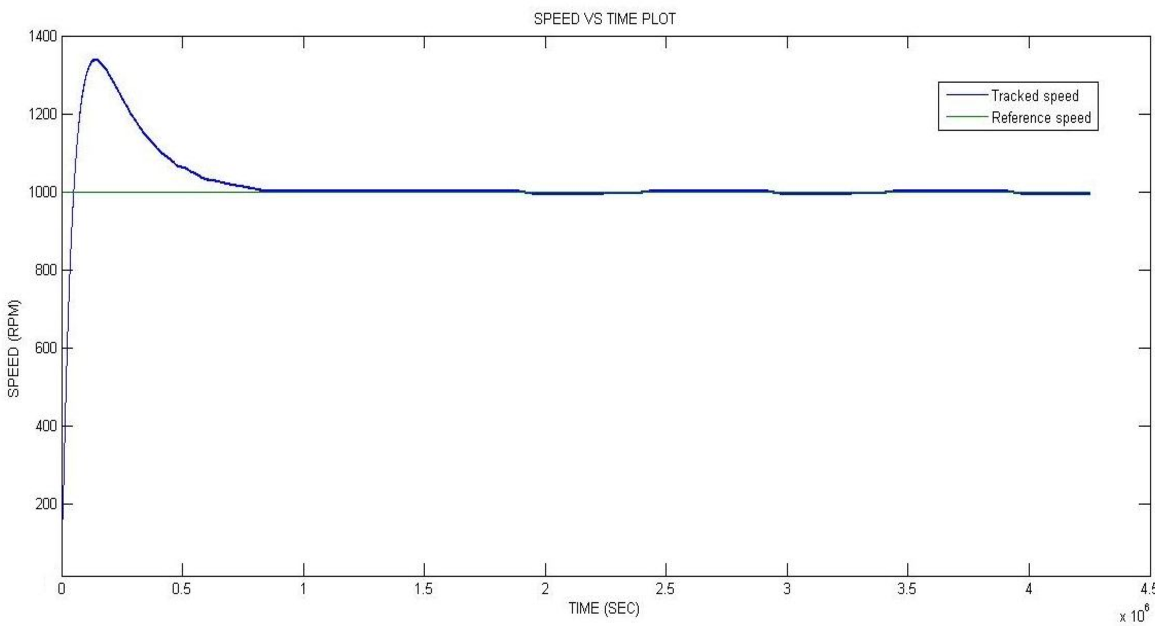


Fig. 10 Motor speed at 1000 rpm.

Reference speed = 1500 rpm.
Tracked speed = 1500 rpm.

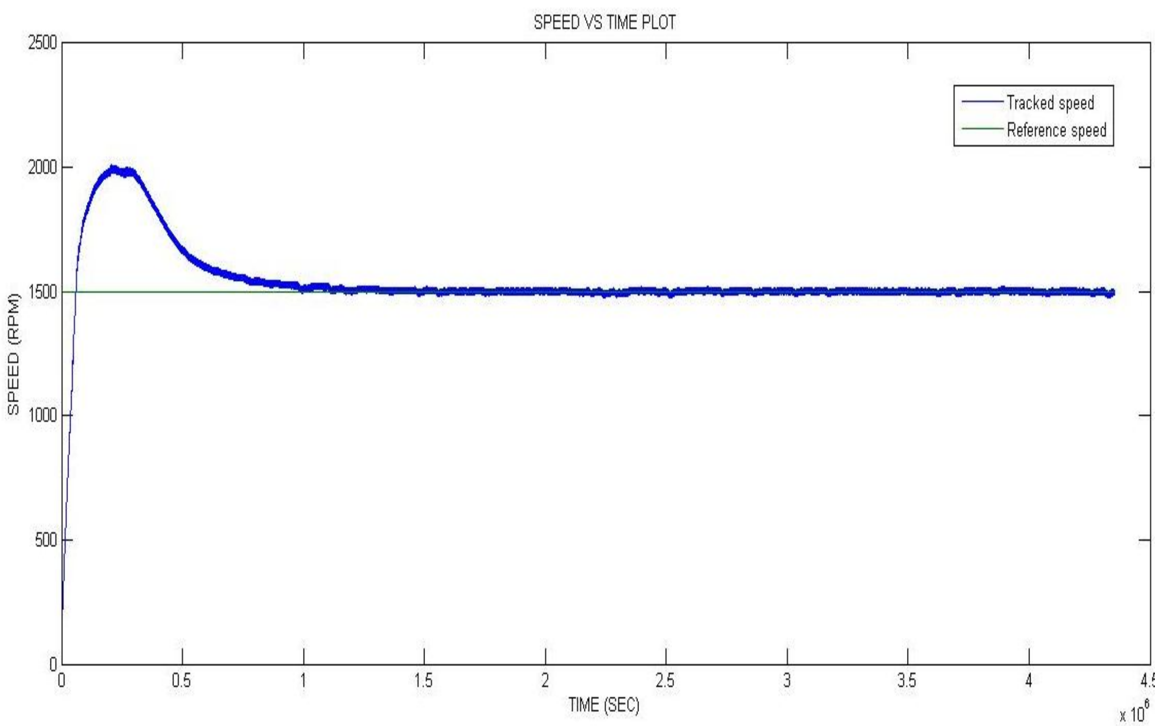


Fig. 11 Motor speed at 1500 rpm.

### *B. Hardware Testing and Experimental Results*

The following figure shows the complete hardware set up of the proposed model in the Electrical Drive Lab. The required input DC supply voltage to the input of the CUK Converter has been fed directly from the main DC supply. The output variable DC voltage of the CUK Converter is then fed to the armature of the Separately Excited DC Motor.

Fig. 12 Complete Hardware experimental framework.

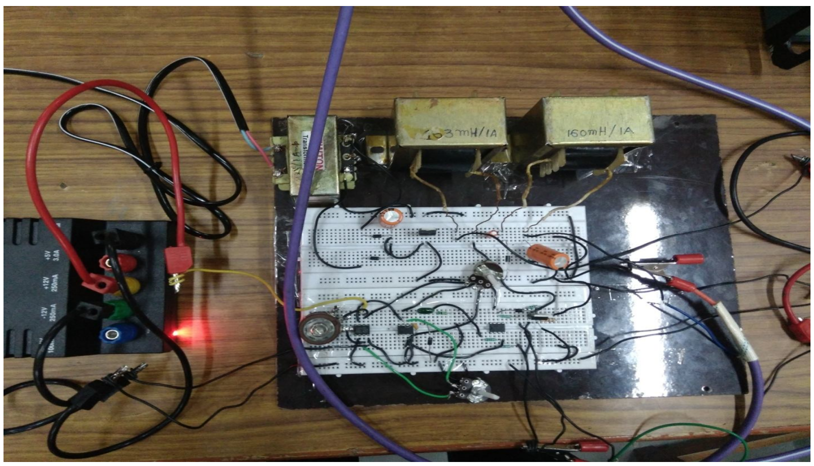

Fig.13 DC-DC CUK Converter

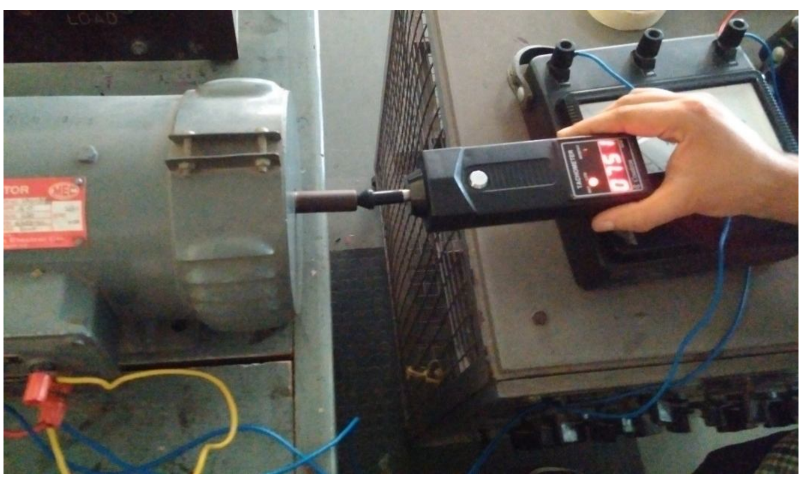

Fig. 14 Measurement of Speed of Separately Excited DC Motor using Tachometer

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The following fig. 15 and 16 given below shows the output of Pulse Width Modulation (PWM) circuit designed above at the duty cycle of 10% and 35% respectively.


Fig. 15 Duty cycle = 10%.


Fig. 16 Duty cycle = 35%

The fig. 17 shows the output voltage waveforms of the combined PID controller shows that for a given error voltage of 2.3V, the output DC voltage so obtained is 6.5V. Further, the fig. 18 shows the output DC voltage of 9.38V for a given error voltage of 3.1V.

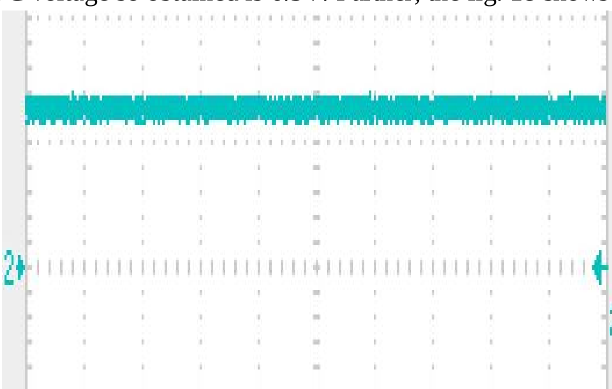

Fig. 17 DC output voltage = 6.5V.

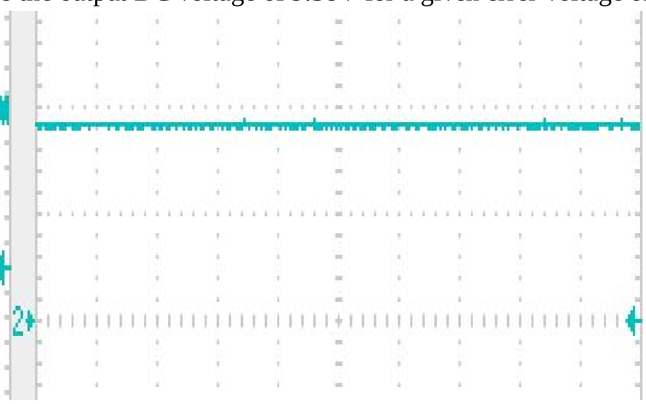

Fig.18 DC output voltage =9.38V.

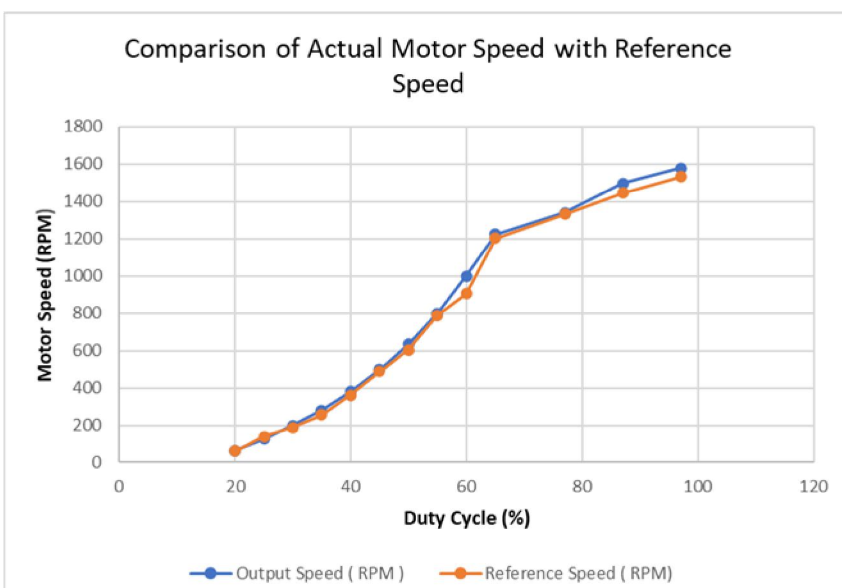


Fig. 19 Comparison plot of actual output speed of motor and the reference speed of the motor with respect to duty cycle.

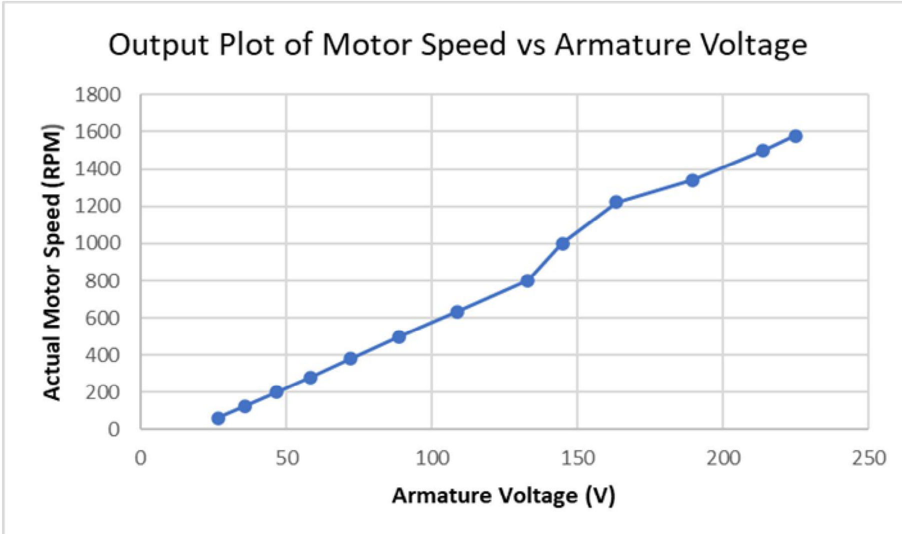


Fig.20 Actual motor speed vs armature voltage plot.

## VI. CONCLUSIONS

The Simulink model of the proposed model is being designed and executed in the MATLAB using PID Controller. Further, the hardware output data have been plotted for comparison between the actual motor speed with the reference speed set for a given duty cycle. The speed of the motor is being measured by using the tachometer available in the lab. It can be clearly seen that the motor speed is coming out to be directly proportional to the duty cycle of the PWM signal. The speed of the motor 1449 is coming out to be at 94.7% duty cycle for a maximum voltage of 225V as per the given ratings of the DC motor chosen. Further the output speed of the motor speed also varies directly in proportion to DC voltage of the CUK Converter which is the armature voltage fed to the Separately Excited DC Motor. Thus, the speed control of Separately Excited DC Motor is being achieved with minor error with regard to the reference speed set in the hardware model.

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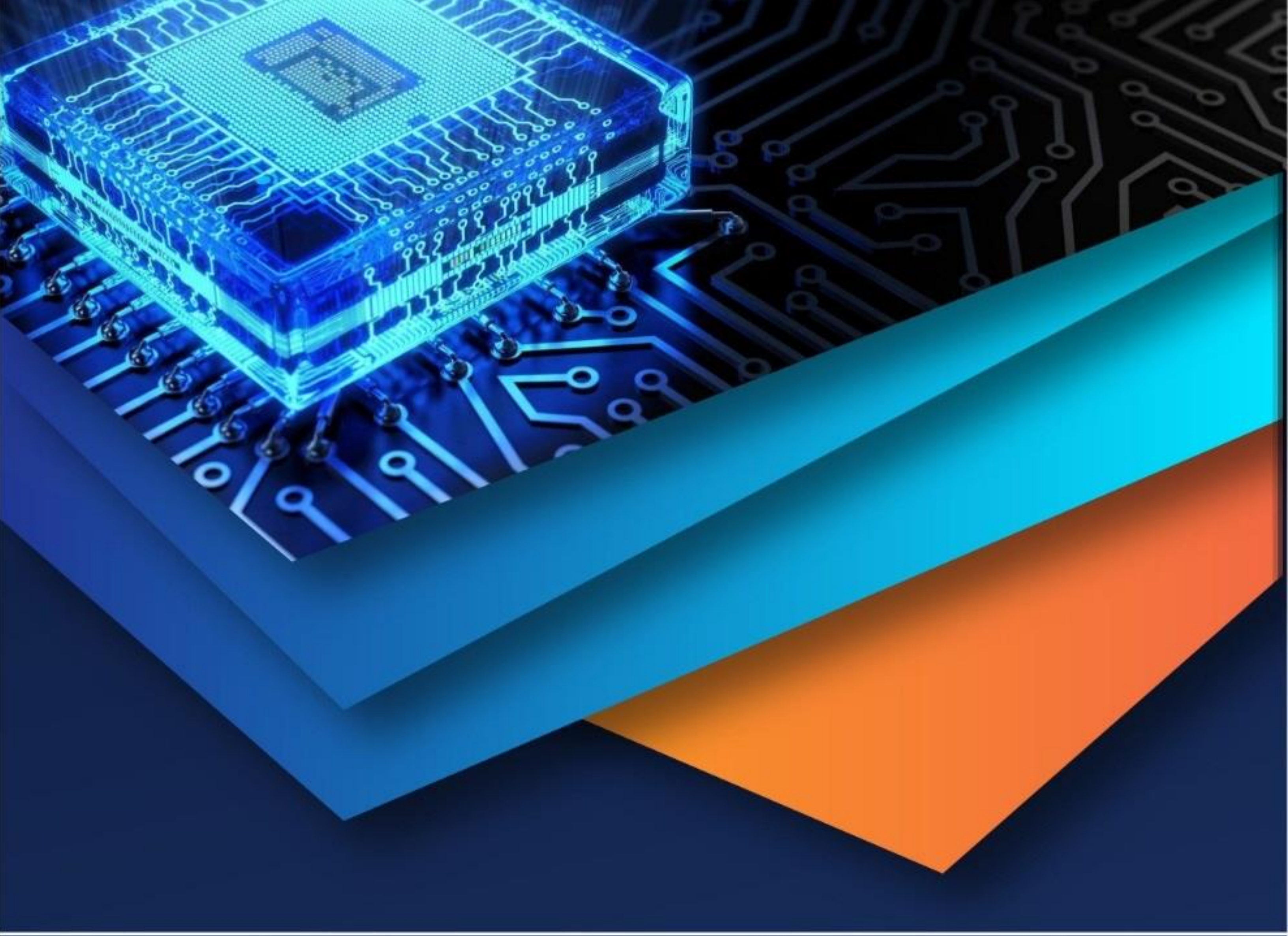


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